Single Slot Coaxial Antenna and NiTi (Nickel Titanium) Loop Antenna Design for ISM (Industrial Scientific Medical) Band Microwave Ablation System

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***Abstract*— For MWA applications in the ISM band, the bioimplant single slot coaxial antenna and NiTi ring antenna are designed. The characteristics of the Sucoform_86 / coaxial cable used in the design of the single slot coaxial antenna are given. Simulation and measurement results of return loss, input impedance, gain, VSWR of the designed bioimplant single slot coaxial antenna are examined. Tumor ablation simulation configuration used, SAR (f = 2.45 GHz) (1gr) simulation result, cut plane image of antenna, curve and multilayered tissues (skin, fat, muscle, tumor), obtained along the curve using heat sources of different strengths Length (mm) - Temperature (Kelvin) graph and Length (mm) - Electric Field (V / m) graph obtained along the curve are presented. The electrical properties of NiTi material have been measured and presented. The return loss, electrical field and orientation parameters of the designed NiTi ring antenna were analyzed and CST drawing of NiTi ring antenna, return loss measurement mechanism and measurement result were presented.**

Keywords*— ablation, microwave heating, bioimplant antennas, NiTi material, specific absorption rate (SAR)

I. INTRODUCTION

Cancer is a chronic degenerative disease that occurs more frequently in adults than children and young people. Breast cancer is the most common type of cancer in women and 23% of all cancer types diagnosed in more than 1.1 million women each year are breast cancer (Saccomandi et al. 2015).

Microwave hyperthermia is a thermal therapy for cancer treatment in which body tissue is exposed to high temperatures. By killing cancer cells, damage to proteins and intracellular structures, hyperthermia can shrink tumors. The effectiveness of hyperthermia depends on the temperature reached during the therapy and the distribution of the microwave thermal field, but is more dependent on the type of microwave radial antenna. Today, implant antennas are used in microwave imaging, observation of cardiac rhythm disorders, cancer diagnosis and treatment methods. As a matter of fact, the applicator must be low-weight, flexible, compliant and also small (Koo et al. 2014).

Frequency-dependent reflection coefficient and SAR pattern within tissue are important for the performance of interstitial antennas. The operating frequency is usually 2.45 GHz, one of the frequencies assigned to the ISM band. (Jesus and Rubio, 2011).

When electromagnetic waves propagate through biological tissues, some of the energy is absorbed by these tissues. Specific absorption rate (SAR) refers to the energy stored per mass unit in a given tissue. The absorbed electromagnetic energy heats the tissue, causing the temperature to rise. Increase in temperature also leads to mechanical and chemical changes in biological tissues (Manzanárez et al. 2018).

SAR is indicated mathematically as follows,

$$SAR = \frac{\sigma}{2\rho}\left|\vec{E}\right|^2 \; [W/kg] \tag{1}$$

where σ is tissue conductivity (S/m), ρ is tissue density $(kg/m\string^3)$.

Combined Electromagnetic Wave Equation and Heat Equation is the EM wave equation and the heat equation in an inhomogeneous environment. The combined EM wave and heat equations are presented as follows in a two-time scale approach.

$$\nabla \times \left(\mu_r{}^{-1}\nabla \times \tilde{E}\right) - \left[\epsilon_r' - j\left(\epsilon_r'' + \frac{\sigma}{\omega\varepsilon_0}\right)\right] k_0^2 \tilde{E} = 0 \tag{2}$$

$$\rho C_p \frac{\partial T}{\partial t} - \nabla.\left(k_{th}\nabla T\right) = Q \tag{3}$$

$$Q = \omega\varepsilon_0\epsilon_r''(T)\frac{|\tilde{E}|^2}{2} \tag{4}$$

In equation 1, E is the electrical vector component of the EM wave within the frequency domain, ω and k_0 are angular frequency and free space wave numbers, respectively. The

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treated material is represented by μ_r, relative magnetic permeability, $\varepsilon_r = \epsilon_r' - j\epsilon_r''$, complex relative dielectric permeability and σ, electrical conductivity. In the heat equation (3), ρ is the local density of the material being processed, C_p and k_{th}, respectively, heat capacity and thermal conductivity, and T is the slowly changing temperature. Heat parameters $\varepsilon_r, \sigma, \rho, C_p$ and k_{th} are considered to have known temperature dependencies.

The EM bandwidth is sufficiently narrow to neglect the frequency change of the electrical permeability, so the wave equation (2) is solved in the frequency domain, while the heat equation (3) is calculated over the slowly varying time interval. The equations (2) and (3) are linked to each other by means of the local EM heating source and through changes in temperature of material parameters $\varepsilon_r, \sigma, \rho, C_p$ and k_{th}.

The vast majority of development of MW ablation technology has been focused on thermal ablation of large unresectable tumors in vascular organs such as the liver. Compared to RF ablation, MW ablation devices enable heating of larger tissue volumes. Researchers have focused on optimizing needle-based MW applicators such as dipole, monopole, and coaxial slot antennas to provide a wide spherical ablation pattern. Both relative permittivity and effective conductivity are dependent on frequency, temperature, and other factors in biological tissues such as water content (Hojjatollah and Punit, 2018).

Furthermore, SAR measurements typically do not account for the changes in antenna radiation pattern due to temperature-dependent changes in tissue dielectric properties. Ablation devices are often characterized in *ex vivo* tissue. The size and shape of the ablation is defined by tissue discoloration at elevated temperatures (Deshazer at al. 2017).

In this paper, a bioimplant single slot coaxial antenna and a NiTi loop antenna design to be utilized as an applicator section of a whole MWA system is proposed for the medical applications in ISM band. In section 2, the geometric models and design principles of the proposed antennas are explained and the results of numerical computation are offered.

II. DESIGNED SINGLE SLOT COAXIAL ANTENNA AND NiTi LOOP ANTENNA, WORKING PRINCIPLES, NUMERICAL COMPUTATION RESULTS

1. Single Slot Coaxial Antenna

Sucoform_86 / coaxial cable, also known as Semi-Rigit Cable, was used in the construction of the first one-slot coaxial antennas produced during this period. The characteristics of this cable are given in Table 1.

Table 1. Sucoform_86 coaxial cable specifications

	**Material**	**Diameter**
Inner Conductor	StCu, Silver plated	0.53 mm
Dielectric	PTFE (polytetrafluor ethylene)	1.65 mm
Cable Sheath	Braid + Band copper, tin plated	2.1 mm

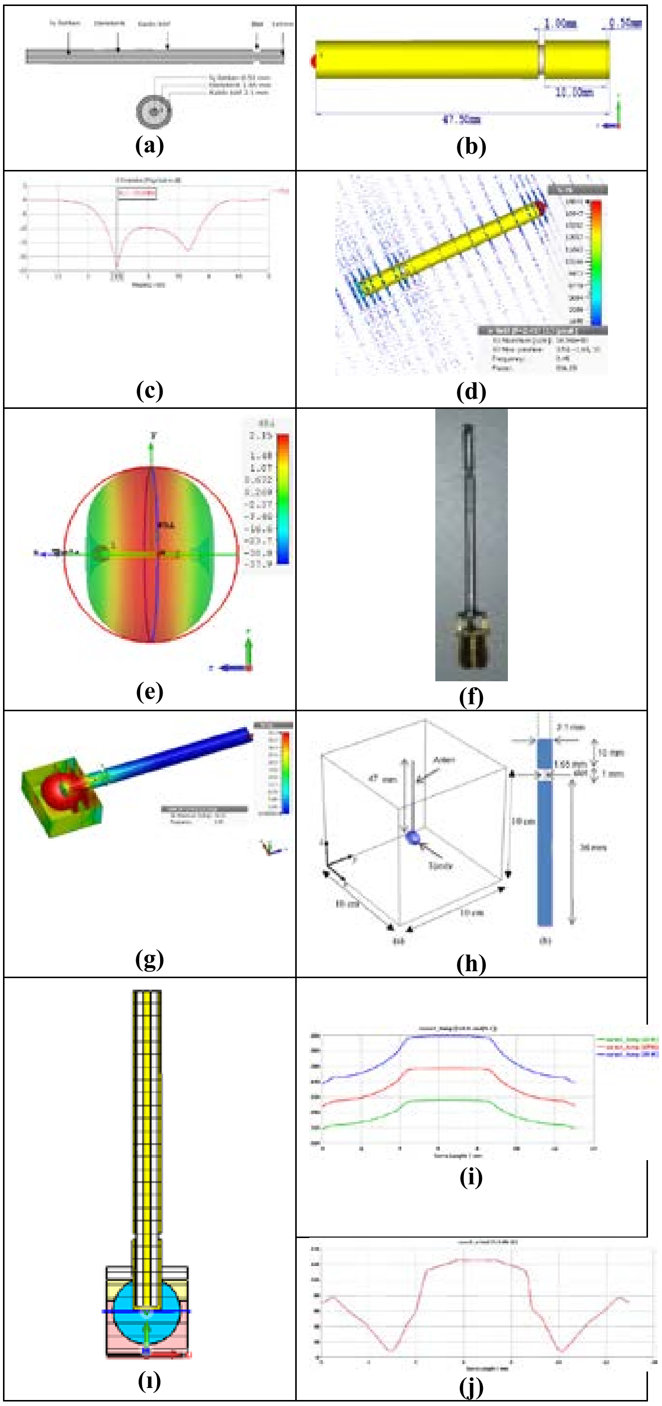


Figure 1. a) Structure and dimensions of single-slot Sucoform_86 coaxial antenna b) CST drawing of single-slot Sucoform_86 coaxial antenna c) S_{11} d) E-Field e) Directivity f) Realized single-slot Sucoform_86 coaxial antenna g) SAR (f = 2.45 GHz) (1gr) h) Tumor ablation simulation configuration and Single slot Sucoform_86 coaxial antenna details i) Cut plane view of antenna, curve and multilayered tissues (skin, fat, muscle, tumor) i) Length (mm) - obtained along the curve using heat sources of different strengths Temperature (Kelvin) graph j) Length obtained along the curve (mm) - Electric Field (V / m) graph

Simulation results Figure 1. As shown in Figure 1. (c), the S_{11} value is -23.37 dB at 2.476 GHz, as shown in Figure 1. (d), the electric field value 2.45 GHz at 18641 (V / m), As shown in Figure 1. (e), the directivity was 2.15 dBi at 2.45 GHz.

As shown in Figure 1. (g), the maximum value of 32.21 W / kg SAR / 1g was obtained by radiating the single-layer Sucoform_86 coaxial antenna at 2.45 GHz to the three-layer (skin, fat, muscle) tumor tissue model. As can be seen, the maximum SAR value was obtained on tumor tissue. As shown in Figure 1. (i), the heat flow of the heat source was applied as 10 W, 15 W and 20 W respectively and the length (mm) - Temperature (Kelvin) graphs obtained along the curve are shown together. Room temperature was taken as 19.95 ℃ (293.1 K). The temperature ranges were 340 - 355K (46.9 - 61.9 °C) for 20 W, 333 - 344K (39.9 - 50.9 °C) for 15 W, and 325 - 334K (31.9 - 40.9 °C) for 10 W.

2. Performance Results Of Single Slot Coaxial Antenna

Performance results of single slot coaxial antenna are presented in Table 2.

Table 2. Single slot coaxial (Sucoform-86) antenna performance results

	SINGLE SLOT COAXIAL ANTENNA	
	Simulation	**Measurement**
Material	Inner Conductor, StCu Dielectric, PTFE Cable sheath, copper, tin coated	
Return loss @ fr	-23 dB @ 2.47 GHz	-18dB@2.45GHz
Input impedance@ fr	57 + 4j @ 2.45 GHz	-----
Gain @ fr	2.105 dB @ 2.45 GHz	2 dB @ 2.45 GHz
HPBW (@ -3dB)	80.4 Deg	90 Deg
Bandwidth (@ -10dB)	600 MHz	550 MHz
VSWR (Sim.)@ fr	< 1.2	< 1.2
Resonance frequency (GHz)	2.47 GHz	2.45 GHz
Group delay	1.2ns	1.5ns
Structure	FR4 & Cu	FR4 & Cu
Connector	Cu- Female	Cu- Female
Dimensions	15mm × 37mm 1.6mm	15mm × 37mm 1.6mm
Weight	-	--

Sucoform_86 / 50Ω coaxial cable was used in the construction of the single slot coaxial antenna produced during this period. The characteristics of this cable are given in Table 1.

3. NiTi Loop Antenna

In this study, NiTi material which is lighter, more resistant to corrosion, has good conductivity, can be used in wide bandwidths, has superior mechanical and biocompatibility properties and experimental preliminary demonstrations have been made.

Some simulation and measurement results showing that NiTi alloy can be used in this subject have been obtained as preliminary study and the measurement results are presented in Table 3 (Kaya at al. 2015).

Table 3. Electrical performance for NiTi material

	Temperature (℃)	Ni50Ti50 Austenite	Ni54Ti46 Austenite	Ni49.2Ti50.8 Austenite	Ni45Ti55 Austenite
WxL (mm)	+25	5x50	6x21	8x40	8x50
T (mm) Weight (g)	+25	0.25 1.5	0.42 1.2	1.41 1.2	0.63 1.1
$\partial R_A/\partial t$ ($\frac{m\Omega}{°C}$)	+25	0.9	1.1	0.9	1.2
Resistance (Ω)	+25	0.160	0.115	0.106	0.121
Rated current	+25	5A	5A	5A	5A
Rated voltage	+25	1.22 V	1.23 V	1.22 V	1.32 V
Power Consumption (Watt)	+25	≈ 7W	≈ 7W	≈ 7W	≈ 7W
Resistance (ohm.cm)	+25	0.00038	0.00140	0.00301	0.00130
Conductivity (S/M)	+25	263400	73420	33240	76920

The values of *Ni50Ti50* alloy that we use to make antennas are $\sigma = 263200$ S/m, Rho $= 6450$ kg/m^3, Young modulus = 114 GPa and thermal expansion coefficient $= 10.(1e-6/K)$. It is preferred because of its high strength, durability and conductivity. The conductivity is $1.2 * 10^{-6} - 2 * 10^{-6}$ (S/m).

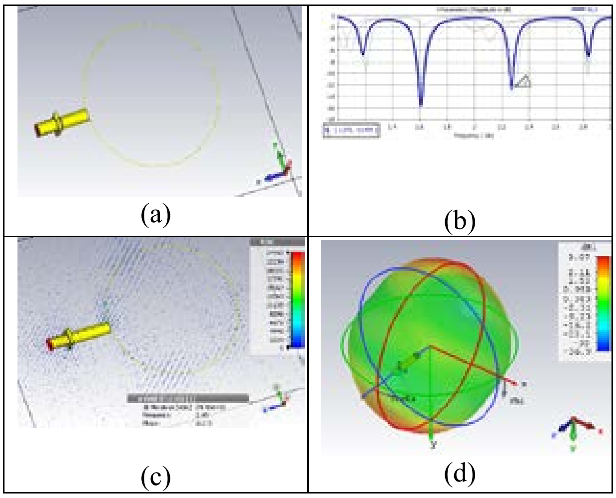
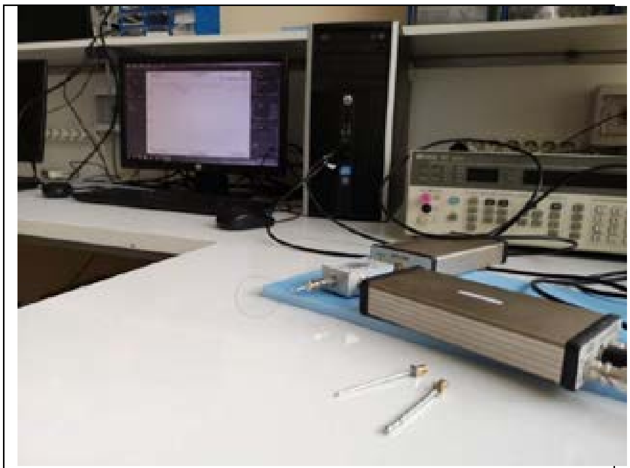


Figure 2. a) CST drawing of the NiTi Ring Antenna b) S_{11} (c) E-Field d) Directivity

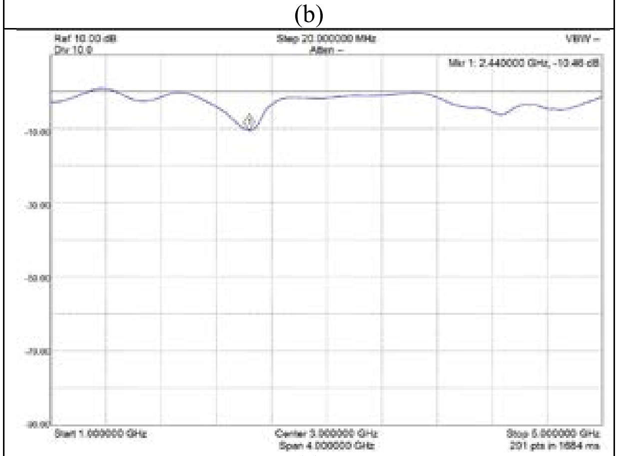
Simulation results in Figure 2. As shown in Figure 2.(b), the S_{11} value is -12.459 dB at 2.23 GHz, as shown in Figure 2. (c) the electric field value 2.45 GHz at 24463 (V / m), As shown in Figure 2. (d), the directivity was 3.07 dBi at 2.45 GHz.

The diameter of the ring portion of the implemented NiTi Ring antenna is 35 mm and the length of the coaxial antenna forming the feed portion is 15 mm. Considering that the wavelength for 2.45 GHz is 122 mm, the feed portion is about one-eighth of the wavelength and the diameter of the NiTi ring is about a quarter of the wavelength.



(a)

(b)



(c)

Figure 3. 2.45 GHz NiTi Ring Antenna 's return loss measuring device and measurement result

Figure 3. (a) and Figure 3. (b) show the return loss measurement device. As shown in Figure 3. (c), the return loss of the NiTi Ring Antenna, designed by adding NiTi wire to the Sucoform - 86 coaxial cable end, was measured as -10.46 dB.

III. CONCLUSION

Hyperthermia was performed in muscle tissue phantom fluid (at 2.45 GHz) with the designed single slot coaxial antenna. When PA output power of 20.48 W is used, it is observed that the temperature range of 41 °C - 44 °C which is the temperature range of hyperthermia is reached at approximately 42 s. NiTi ring antenna was applied MWA on freshly cut bovine liver. As a result of applying approximately 50 W sine wave to our antenna for about 5 minutes, 102 °C temperature was measured in the red region where the highest temperature was. In this paper, as a result of numerical computation, the proposed bioimplant single slot coaxial antenna design is also expected to provide significant technological advances in terms of medical engineering applications. On the basis of this study, the bioimplant single slot coaxial antenna can be conveniently produced to bring out an improved medical device in the cancer therapy due to the commercially available materials. A good agreement was obtained between numerical and experimental results. The results emphasize the ability of the single-slot coaxial antenna to produce high SAR values around the slot and therefore in the tumor site, and conversely very low SAR values along the antenna length. This SAR distribution makes the single-slot coaxial antenna suitable for MWA applications because it allows the heating arrangement to focus close to the slot portion of the antenna and minimizes unwanted tissue heating along the antenna length. After examining the basic physical properties, mechanical properties and electrical performance of NiTi materials, NiTi ring antenna was designed by adding NiTi wire to the end of the Sucoform - 86 coaxial cable. The designed NiTi ring antenna is thought to be an alternative antenna that can be used especially in MWA applications where wide ablation region is aimed.

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